

Inelastic Collisions in Optically Trapped Ultracold Metastable Ytterbium

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We report measurement of inelastic loss in dense and cold metastable ytterbium ($\text{Yb}[^3P_2]$). Use of an optical far-off-resonance trap enables us to trap atoms in all magnetic sublevels, removing multichannel collisional trap loss from the system. Trapped samples of $\text{Yb}[^3P_2]$ are produced at a density of $2 \times 10^{13} \text{ cm}^{-3}$ and temperature of $2 \text{ } \mu\text{K}$. We observe rapid two-body trap loss of $\text{Yb}[^3P_2]$ and measure the inelastic collision rate constant $1.0(3) \times 10^{-11} \text{ cm}^3 \text{ s}^{-1}$. The existence of the fine-structure changing collisions between atoms in the 3P_2 state is strongly suggested.

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There is increasing interest in ultracold two-electron atoms [1, 2], such as the alkaline earth metals (e.g. Ca and Sr) and Yb. In particular, novel characteristics of the metastable 3P_2 atoms have recently attracted attention, both for applications and for the study of their collisional properties [3]. These atoms are set apart from the more commonly studied alkali metal atoms because collisions between 3P_2 atoms are intrinsically anisotropic. Recent theory has investigated the effects of this anisotropy, including its interplay with magnetic field effects, which enable novel control of the scattering length [4], and multichannel collisions due to a strong coupling among the partial waves of relative motion [5, 6]. Also, the magnetic dipole-dipole interaction between 3P_2 atoms is 9 times larger than that between alkali metal atoms. This has led to theoretical predictions such as novel quantum phases and use in quantum information systems [7, 8].

In order to move toward study of these new possible features of 3P_2 atoms, several laboratories have realized laser cooling and trapping of metastable two-electron atoms. Ca and Sr atoms decaying to the 3P_2 state from the 1P_1 state, which is the upper state in the $^1S_0 \leftrightarrow ^1P_1$ magneto-optical trap (MOT) transition, have been successfully trapped in a magnetic trap [9]. Also, a MOT operating on the $^3P_2 \leftrightarrow ^3D_3$ transition has been used to load a magnetic trap [10]. In spite of successes of these approaches, evaporative cooling of 3P_2 atoms in a magnetic trap to reach Bose-Einstein condensation (BEC) turned out to be unsuccessful due to trap loss caused by strong multichannel collision processes [5]. More recently, a similar large inelastic collision rate in $\text{Ca}[^3P_2, m_J=2]$ was observed [11].

The loss induced by multichannel collisions in a magnetic trap can be overcome by employing, instead of a magnetic trap, an optical far-off-resonance trap (FORT). According to Ref. [12], the FORT wavelength can be chosen so that atoms in every magnetic sublevel of the 3P_2 state can be trapped with the same strength. As a result, although multichannel collisions can still occur,

which distributes the atoms over the different magnetic sublevels, they will not lead to trap loss. Thus, any trap loss observed in such a trap must be due to a different physical mechanism. Study of these collisional properties is crucial to understanding the physics of these important class of atoms and states.

In this paper, we report both the experimental realization of optical trapping (FORT) of ultracold $^{174}\text{Yb}[^3P_2]$ atoms at high atom number density and the quantitative measurement of inelastic collisions. In contrast to previous methods, we first trap atoms and perform evaporative cooling using $\text{Yb}[^1S_0]$ in the FORT. We optically excite $\text{Yb}[^1S_0]$ to the 3P_2 state to obtain ultracold trapped $\text{Yb}[^3P_2]$, achieving a number density of $2 \times 10^{13} \text{ cm}^{-3}$ at a temperature of $2 \text{ } \mu\text{K}$ with phase space density (PSD) of 0.01. Our newly achieved atom number density is larger than the previous work by an order of three [10]. We also measured a large two-body inelastic collision rate in the FORT which we interpret as fine-structure changing collisions in this ultracold temperature regime. Although fine-structure changing inelastic collisional properties have previously been investigated for $\text{Mg}[^3P_J]$, $\text{O}[^3P_J]$, $\text{Sc}[^2D_J]$, and $\text{Ti}[^3F_J]$ colliding with closed shell atoms [13, 14, 15, 16], they had not been seen in collisions between 3P_2 atoms. While the recent experiment of magnetically trapped Ca atoms studied multichannel collisions between 3P_2 atoms and discussed the possibility of the fine-structure changing process [11], we believe that our work is the first definite experimental measurement of this process between 3P_2 atoms.

Our typical procedure to prepare and detect atoms in the 3P_2 state is summarized in Fig.1. At the first stage A, we prepare cold ^{174}Yb atoms in the ground state in the FORT by almost the same method as that of our previous works [17, 18] which is briefly summarized here. With about 10 sec loading, we typically collect 10^7 Yb atoms in the ground state at a temperature below $50 \text{ } \mu\text{K}$ by the MOT using the narrow intercombination transition $^1S_0 \leftrightarrow ^3P_1$. These atoms are then transferred to a single

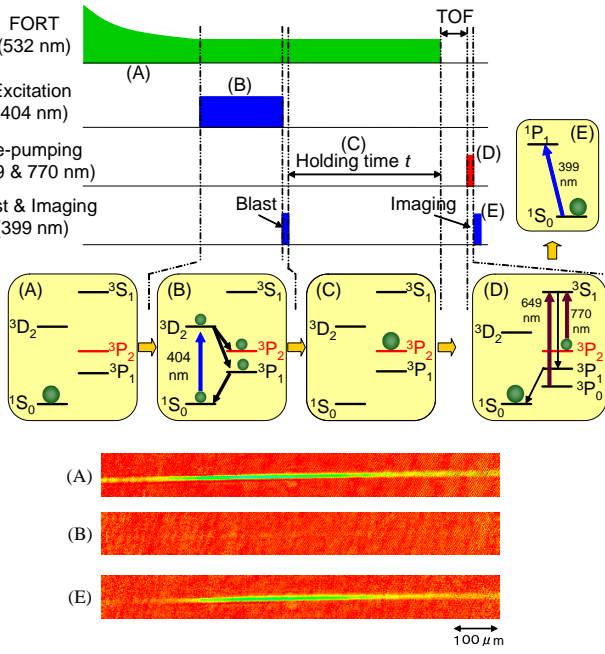


FIG. 1: (color online). Experimental procedures to excite atoms to the 3P_2 state. Absorption images of atoms in the ground state at stages A, B, and E are also shown below. (A): Yb atoms trapped in a MOT are cooled by evaporative cooling. (B): Then atoms are optically excited to the 3P_2 state in the FORT via the intermediate 3D_2 state and subsequent spontaneous decay $^3D_2 \rightarrow ^3P_2$. Atoms remaining in the ground state are blown by a short blast laser pulse just after the excitation. Thus no atoms in the ground state are observed in the CCD image at this stage. (C): Metastable atoms are left in the FORT during the holding time t . (D): After a TOF time, metastable atoms are repumped to the ground state by 770 nm ($^3P_2 \leftrightarrow ^3S_1$) and 649 nm ($^3P_0 \leftrightarrow ^3S_1$) laser pulses of 100 μ s and (E) detected by the absorption imaging.

or crossed FORT created by focused diode-pumped solid state 10 W-lasers at 532 nm. After carrying out evaporative cooling by gradually reducing the trap depth, we typically have 10^6 atoms at a temperature of 30 μ K in the single FORT. When we use a crossed FORT configuration and perform evaporative cooling, a temperature of atoms reaches below 1 μ K.

At the next stage B, we optically excite atoms to the 3P_2 state in the FORT. We use the intermediate 3D_2 state for the excitation (transition linewidth: 350 kHz [19]) and the subsequent spontaneous decay to the 3P_2 state with the lifetime 460 ns of the 3D_2 state. Although some atoms in the 3D_2 state can also decay to the 3P_1 state, they immediately decay to the ground state with the lifetime 875 ns of the 3P_1 state and are re-excited to the 3D_2 state. Thus, after iterating this excitation cycle for several times, we can transfer all atoms to the 3P_2 state typically within 5 ms. In order to efficiently excite atoms, we stabilize a blue GaN laser diode (404

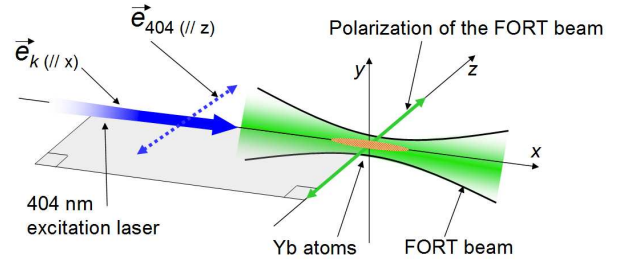


FIG. 2: (color online). Experimental setups are schematically shown. The \vec{e}_{404} and $\vec{e}_k = \vec{k}/|\vec{k}|$ are the polarization and the wavenumber vector of the 404 nm excitation laser.

nm) by an external cavity laser diode system combined with an optical feedback technique [20]. The resulting linewidth is narrowed to 1 MHz for 0.5 s. The excitation laser is superposed with the FORT laser (see Fig. 2) and the peak intensity at atoms reaches 1.5 W/cm². Just after the excitation, we irradiate a short blast pulse which blows remaining atoms in the ground state by using the strong $^1S_0 \leftrightarrow ^1P_1$ transition.

The $^1S_0 \leftrightarrow ^3D_2$ transition (404 nm) is the electric quadrupole (E2) transition. In this experiment, as shown in Fig. 2, we set $\vec{e}_{404} \parallel z$ and $\vec{e}_k \parallel x$, where \vec{e}_{404} and $\vec{e}_k = \vec{k}/|\vec{k}|$ are the polarization and the wavenumber vectors of the 404 nm excitation laser. Thus atoms are excited to the 3D_2 , $m = \pm 1$ states due to the selection rule and subsequently decay to all the magnetic sublevels of the 3P_2 state with the ratio 3 : 1 : 2 for $|m|=0, 1$, and 2 sublevels of the 3P_2 state, respectively.

At the stage C, we hold metastable atoms in the FORT for a time t . Then, at the stage D, in order to measure the temperature and the number of atoms in the 3P_2 state with a time-of-flight (TOF) technique, we rapidly repump all the metastable 3P_2 atoms to the ground state after a TOF time. A 770 nm ($^3P_2 \leftrightarrow ^3S_1$) resonant pulse excites atoms from the 3P_2 state to the 3S_1 state, from which all the 3P_2 , 3P_1 , and 3P_0 states are populated through spontaneous decay. By simultaneous application of a 649 nm ($^3P_0 \leftrightarrow ^3S_1$) resonant pulse, all atoms return through the 3P_1 state to the ground state where we can use an absorption imaging technique using the strong cyclic $^1S_0 \leftrightarrow ^1P_1$ transition at the stage E. Since 100 μ s duration for the repumping procedure is short enough compared with a typical TOF time, we can safely regard that the observed atomic distribution precisely reflects that of atoms in the 3P_2 state.

We first measured a trap frequency for the atoms in the 3P_2 state in the single FORT by using a parametric resonance technique [21], where atoms are heated at the modulation frequency $\omega = 2\omega_{\text{trap}}/n$ with ω_{trap} the trap frequency and n an integer. To this end, the FORT power was modulated at the stage C (see Fig. 1). Here we took special care about the cancellation of a magnetic field since the light shifts due to the FORT beam in the pres-

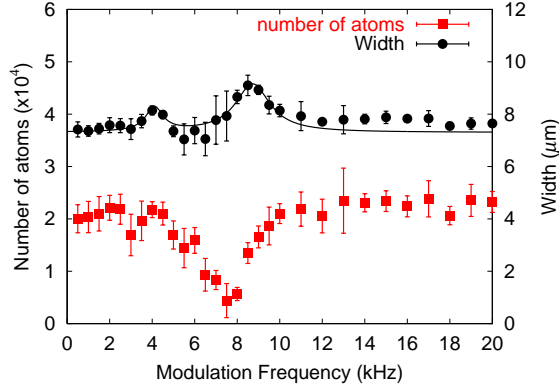


FIG. 3: (color online). Measurement of the trap frequency of the 3P_2 state by using the parametric resonance technique. Number of trapped atoms and the width of the atomic cloud are plotted as a function of the modulation frequency.

ence of a large magnetic field are quite sensitive to the relative orientation between the magnetic field and the FORT polarization [22]. We measured the number of remaining atoms and the width of the atomic cloud, which are shown in Fig. 3. Two resonance signals corresponding to $n=1$ and 2 are clearly observed at 8.6 and 4.3 kHz, respectively, while the trap frequency of the 1S_0 state in this condition is 3.9 kHz. The resonance frequency is determined by fitting a Lorentzian function to the width of atomic clouds. Since all the magnetic sublevels of the 3P_2 state are populated in this measurement and in fact we experimentally confirmed that the atoms in every sublevel are trapped, their trap frequencies can be thought to coincide with each other within the resolution of this measurement. This result is consistent with the measurement of polarizabilities of magnetic sublevels of the 3P_2 state using the ultranarrow $^1S_0 \leftrightarrow ^3P_2$ transition in our different work, which indicates that the difference of the trap frequency between magnetic sublevels is less than 1 kHz [12]. Thus, in the following discussion, we consider that the trap depth of all magnetic sublevels of the 3P_2 state is the same. With this information on the trap, we can accurately estimate a density.

We successfully obtain high density ultracold metastable $\text{Yb}[^3P_2]$ by exciting pre-cooled $\text{Yb}[^1S_0]$ in a crossed FORT. These atoms are prepared at a density of $2 \times 10^{14} \text{ cm}^{-3}$ and at a temperature of less than $0.7 \text{ } \mu\text{K}$. During excitation from the ground state to the 3P_2 state (through the intermediate 3D_2 state), the atoms suffer from heating due to the spontaneous decay. As a result, the density of atoms decreases and the temperature increases, resulting in density $n = 2 \times 10^{13} \text{ cm}^{-3}$, temperature $T = 2.0 \text{ } \mu\text{K}$ and PSD = 0.01. This is the highest density and lowest temperature ever achieved for 3P_2 atoms. Although in principle PSD could be increased by direct evaporative cooling of the $\text{Yb}[^3P_2]$ atoms, we found this impossible due to an inelastic

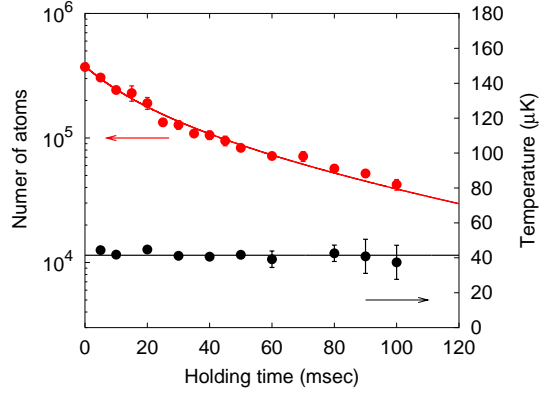


FIG. 4: (color online). Number of atoms and temperature of atoms in the FORT are plotted as a function of holding time. The non-exponential rapid decay can be well described by the Eq.(1), which implies the large two-body loss rate of metastable atoms. Almost constant temperature during the measured holding time indicates that the system is in the thermal equilibrium.

collisional process which we identify as fine-structure changing collisions.

We studied inelastic loss by measuring the number density decay of $\text{Yb}[^3P_2]$ atoms from a single beam FORT. Figure 4 shows the number of 3P_2 atoms in the FORT as a function of time after loading. Note that the (presumably state independent) one-body trap loss lifetime due to background gas collisions is measured to be 15 s, much longer than the observed trap lifetime. A significant feature of the data is the non-exponential decay of atom number along with the constant temperature of $T = 41 \text{ } \mu\text{K}$. Our model for atom loss includes a combination of one-body loss and two-body loss, as embodied in the following equation for atom number versus time.

$$\frac{dN}{dt} = -\Gamma N - \beta' N^2, \quad (1)$$

where Γ is the one-body loss rate and β' is the measured two-body atom loss rate. The solid line in Fig. 4 for data of the number of atoms in the FORT is a fit by Eq. (1). β' is related to the density related (volume independent) two-body loss rate coefficient β by $\beta = \beta' V_{\text{eff}}$, where V_{eff} is the effective volume of the atoms. In the present experiment, the volume can be well approximated by a cylinder with the size of the FORT beam [23]

$$V_{\text{eff}} = \pi \omega_0^2 z_R \ln \left(\frac{\eta}{\eta - 1} \right) \sqrt{\frac{1}{\eta - 1}}, \quad (2)$$

where ω_0 and z_R are the beam waist and the Rayleigh length of the FORT beam, respectively. $\eta (= U_0/(k_B T))$ is the ratio of the trap depth U_0 to the temperature T , and k_B is the Boltzmann constant. From the measured trap frequency, the trap depth is found to be $U_0/k_B = 193 \text{ } \mu\text{K}$ for all magnetic sublevels and thus $\eta = 4.7$ which remains constant throughout the 120 ms holding time.

The two-body collisional loss of atoms from the trap can be due to elastic and inelastic processes, identified as elastic (β_{el}) and inelastic (β_{in}) collision rates, respectively. Under thermal equilibrium conditions, the relation between the observed two-body decay rate β and the elastic β_{el} and inelastic β_{in} collision rate are described by

$$\beta_{\text{in}} = \frac{1}{f\gamma + 1}\beta, \quad \beta_{\text{el}} = \frac{\gamma}{f\gamma + 1}\beta, \quad (3)$$

where f is the evaporation fraction and $\gamma \equiv \sigma_{\text{el}}/\sigma_{\text{in}}$ is the ratio of the elastic to inelastic cross sections [24]. All of these parameters f and γ are functions of only η . Thus, by slightly modifying the method in [24], we can estimate both the inelastic scattering rate $\beta_{\text{in}} = 1.0(3) \times 10^{-11} \text{ cm}^3\text{s}^{-1}$ and the elastic one $\beta_{\text{el}} = 2.3(6) \times 10^{-11} \text{ cm}^3\text{s}^{-1}$ for the temperature 41 μK . The elastic binary collision rate can be independently investigated by the cross-dimensional relaxation measurement [25] and the result was consistent with the above estimation.

Considering the suppression of multichannel collisional loss in our FORT which can trap atoms in every magnetic sublevel of the 3P_2 state with zero magnetic field, the observed inelastic collision rate is anomalously large. Thus a different inelastic collision process – fine-structure changing collisions – is strongly suggested. The previous theoretical works revealed details of fine-structure changing transitions in collisions of $\text{Mg}[^3P_j]$, $\text{O}[^3P_j]$, $\text{Sc}[^2D_j]$, and $\text{Ti}[^3F_j]$ atoms with closed-shell atoms at a high temperature [13, 14, 15, 16]. However, there has not been no theoretical work on the fine-structure changing collisions between atoms in the 3P_2 state at ultralow temperature achieved in the present work. As our experimental results suggest, further theoretical investigation is warranted.

In conclusion we have optically trapped high density metastable ytterbium atoms in the FORT. The achieved number density is $2 \times 10^{13} \text{ cm}^{-3}$ at a temperature 2 μK . The non-exponential rapid loss of atoms in the FORT at a constant temperature is observed, and then a large inelastic binary collision rate constant is measured. We interpret this as fine structure changing collisions between 3P_2 atoms.

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